

Experimental Study on Strength and Geomechanical Behavior of Fly Ash Based Geopolymer Stabilized Clay

KARTHICK M¹

¹ Student, Department of Civil Engineering (Geotechnical Engineering), Government College of Technology


SATHEES KUMAR V²

² Associate Professor, Department of Civil Engineering (Geotechnical Engineering), Government College of Technology



<https://doi.org/10.55041/ijstmt.v2i5.185>

Cite this Article: M, K. (2026). Experimental Study on Strength and Geomechanical Behavior of Fly Ash Based Geopolymer Stabilized Clay. International Journal of Science, Strategic Management and Technology, 02(05). <https://doi.org/10.55041/ijstmt.v2i5.185>

License:  This article is published under the Creative Commons Attribution 4.0 International License (CC BY 4.0), permitting use, distribution, and reproduction in any medium, provided the original author(s) and source are properly credited.

ABSTRACT

Expansive clay soils possess low shear strength, high compressibility, and excessive swelling characteristics, which create severe challenges in geotechnical engineering applications. Conventional stabilization methods using cement and lime improve soil properties but contribute significantly to carbon emissions and environmental degradation. In the present study, an eco-friendly stabilization technique using fly ash-based geopolymer activated with sodium hydroxide (NaOH) was investigated to improve the strength and geomechanical behavior of expansive clay soil. Class F fly ash and NaOH solution were used as geopolymeric binders in different proportions. Three combinations consisting of 5% fly ash + 8 M NaOH, 10% fly ash + 10 M NaOH, and 15% fly ash + 12 M NaOH were prepared and tested. Preliminary tests including specific gravity, Atterberg limits, compaction characteristics, and Unconfined Compressive Strength (UCS) were carried out on untreated soil. Stabilized specimens were cured for seven days and subjected to UCS testing. The untreated clay exhibited a UCS value of 42 kPa, whereas stabilized samples achieved significant improvements. The optimum mix containing 10% fly ash with 10 M NaOH produced the highest UCS value of 185 kPa, corresponding to approximately 340% improvement over untreated clay. The results indicate that fly ash-based geopolymer stabilization considerably enhances the strength, stiffness, and load-bearing capacity of expansive clay while reducing plasticity. The study confirms that geopolymer stabilization can serve as a sustainable and environmentally friendly alternative to conventional chemical stabilizers in geotechnical engineering applications.

Keywords: Expansive clay, Fly ash, Geopolymer, Sodium hydroxide, Soil stabilization, UCS, Geomechanical behavior.

1. INTRODUCTION

Expansive soils are among the most problematic geomaterials encountered in civil engineering practice due to their excessive swelling and shrinkage characteristics caused by seasonal moisture variation. These soils undergo considerable volume changes when subjected to wetting and drying cycles, leading to differential settlement, pavement cracking, foundation distress, slope instability, and structural damage. Expansive clay deposits are commonly found in many parts of India and represent a major challenge in the design and construction of transportation and geotechnical infrastructure. The engineering behavior of expansive clay is primarily governed by mineralogical composition, moisture content, density, and clay particle arrangement. Soils containing montmorillonite minerals generally exhibit high plasticity, low shear strength, high compressibility, and significant swelling potential. Such characteristics make untreated expansive soils unsuitable for supporting foundations, pavements, retaining structures, and embankments. In recent years, sustainable and environmentally friendly stabilization methods have gained considerable attention in geotechnical engineering. Among these methods, geopolymer technology has emerged as a promising alternative due to its low carbon footprint, excellent mechanical performance, and effective utilization of industrial by-products. Geopolymers are

inorganic aluminosilicate materials produced through the chemical reaction between silica–alumina rich source materials and alkaline activators. Fly ash generated from thermal power plants contains reactive silica and alumina capable of forming geopolymeric gel when activated using alkaline solutions such as sodium hydroxide (NaOH). The geopolymerization process produces strong three-dimensional aluminosilicate networks that enhance particle bonding and improve the strength and durability characteristics of soils. Fly ash–based geopolymer stabilization offers several advantages over conventional stabilization techniques:

- Reduction in environmental pollution through utilization of industrial waste.
- Lower greenhouse gas emissions compared to cement production.
- Improvement in soil strength and stiffness.
- Reduction in plasticity and swelling behavior.
- Enhanced durability against environmental exposure.
- Sustainable and economical construction practice.

The mechanism of geopolymer stabilization involves dissolution of silica and alumina from fly ash under highly alkaline conditions, followed by polycondensation reactions forming aluminosilicate gel structures. These gel structures fill soil voids and bind particles together, thereby increasing density, stiffness, and compressive strength.

Several studies have reported that geopolymer stabilized soils exhibit superior mechanical performance and durability. However, the strength improvement largely depends on factors such as fly ash content, activator concentration, curing duration, moisture content, and soil mineralogy. Optimization of these parameters is therefore essential for practical field applications.

2. OBJECTIVES

The major objectives of the present investigation are:

1. To evaluate the compressive strength of clay soil stabilized with fly ash–NaOH geopolymer using UCS test specimens.
2. To study the influence of varying fly ash and NaOH concentrations on the strength characteristics of expansive clay.
3. To compare the performance of geopolymer stabilized clay with untreated clay.
4. To identify the optimum fly ash–NaOH combination for maximum strength improvement.
5. To assess the suitability of fly ash–based geopolymer as a sustainable alternative to conventional soil stabilizers.

3. LITERATURE REVIEW

Several researchers have investigated the effectiveness of industrial by-products and geopolymer binders for stabilization of expansive soils.

Adem Isik (2025) investigated the compressive strength behavior of clay soil stabilized using construction and demolition waste-based geopolymer binders. The study reported significant improvement in compressive strength with increasing curing duration and alkali activator concentration.

Luo et al. (2022) studied the sulfate resistance of slag-fly ash geopolymer stabilized soils and observed improved durability under sulfate-rich environmental conditions.

Hayder H. Abdullah and Mohamed A. Shahin (2023) evaluated the geomechanical behavior of soft clay treated with fly ash–based geopolymer for deep mixing applications. Their research demonstrated considerable enhancement in strength and stiffness characteristics.

Abdullah and Shahin (2023) further investigated long-term sulfate attack on geopolymer stabilized clay and reported significant improvement in strength without major volumetric changes.

Mahedi et al. (2020) compared cement, lime, and fly ash stabilization techniques for expansive soils and concluded that fly ash-based treatment can effectively improve soil performance while reducing environmental impact.

Previous studies confirm that geopolymer stabilization improves compressive strength, stiffness, durability, and resistance to environmental degradation. However, limited studies have focused on the combined effect of fly ash and varying NaOH molarity on expansive clay stabilization. Therefore, the present work attempts to bridge this research gap.

4. MATERIALS USED

4.1 Clay Soil

Locally available expansive clay soil was collected from Coimbatore region, Tamil Nadu, India. The soil was air-dried and pulverized before testing. Sieve analysis and index property tests were conducted to determine the engineering characteristics of the soil.

S. No	Property	Value
1	Specific Gravity	2.73
2	Liquid Limit	54%
3	Plastic Limit	11.11%
4	Plasticity Index	42.89%
5	Optimum Moisture Content	18%
6	Maximum Dry Density	1.74 g/cc
7	Cohesion	21 kPa
8	UCS	42 kPa
9	IS Classification	CH

Table 1. Properties of Untreated Clay

The soil was classified as highly plastic clay (CH) according to IS soil classification system.

4.2 Fly Ash

Class F fly ash was used as the primary geopolymeric binder. Fly ash contains high percentages of silica and alumina, which are essential for geopolymerization reactions. The fly ash improves soil bonding and contributes to strength enhancement.

4.3 Alkaline Activator

Sodium hydroxide (NaOH) solution was used as the alkaline activator. NaOH initiates dissolution of silica and alumina from fly ash particles and promotes geopolymeric gel formation.

5. EXPERIMENTAL PROGRAM

5.1 Collection of Soil Sample

The expansive clay soil used in the present study was collected from a locally available site in Coimbatore, Tamil Nadu, India. The collected soil was transported to the geotechnical laboratory in airtight bags to prevent moisture loss. The soil was air-dried under laboratory conditions and pulverized manually to break soil lumps. The processed soil was then passed through a 4.75 mm IS sieve before conducting laboratory tests.

5.2 Characterization of Untreated Soil

The engineering properties of untreated soil were determined through preliminary laboratory testing. The following properties were evaluated:

- Specific gravity
- Grain size distribution
- Liquid limit
- Plastic limit
- Plasticity index
- Standard Proctor compaction characteristics
- Unconfined compressive strength

The soil exhibited high plasticity and low compressive strength, confirming its expansive nature.

5.3 Preparation of Geopolymer Stabilizer

Class F fly ash was selected as the primary aluminosilicate precursor material because of its high silica and alumina content. Sodium hydroxide solution of different molarities was prepared by dissolving NaOH pellets in distilled water. The NaOH solutions were prepared carefully due to the exothermic nature of dissolution. The prepared alkaline solutions were allowed to cool for 24 hours before mixing with soil and fly ash.

The geopolymerization process mainly involved the following stages:

1. Dissolution of silica and alumina from fly ash.
2. Transportation of dissolved species.
3. Polycondensation reaction.
4. Formation of geopolymeric aluminosilicate gel.
5. Hardening and strength development.

5.4 Mix Proportions

Three geopolymer stabilized mixes were prepared using different fly ash contents and NaOH molarities.

Mix ID	Composition
Mix 1	5% Fly Ash + 8 M NaOH
Mix 2	10% Fly Ash + 10 M NaOH
Mix 3	15% Fly Ash + 12 M NaOH

Table 2. Mix Proportions

The selected percentages were based on previous literature studies indicating effective geopolymerization within this range.

5.5 Preparation of Stabilized Specimens

The required quantity of dry soil was weighed and mixed thoroughly with fly ash to achieve uniform distribution. Sodium hydroxide solution was gradually added to the dry mixture while maintaining optimum moisture conditions.

The stabilized mixtures were compacted into cylindrical UCS moulds in multiple layers to minimize entrapped air and achieve uniform density. The specimens were carefully extruded and sealed to prevent moisture loss.

5.6 Curing Procedure

The prepared specimens were cured under laboratory conditions for seven days. Curing plays a critical role in geopolymer stabilization because geopolymeric reactions continue with time, resulting in progressive strength gain.

During curing:

- Moisture evaporation was minimized.
- Temperature variation was controlled.
- Uniform curing conditions were maintained for all specimens.

6. RESULTS AND DISCUSSION

6.1 Unconfined Compressive Strength Results

The UCS values obtained for different stabilized mixes are presented below.

Mix ID	Composition	UCS (N/mm ²)	UCS (kPa)	Observation
Mix 1	5% Fly Ash + 8 M NaOH	0.096	96	Moderate improvement
Mix 2	10% Fly Ash + 10 M NaOH	0.185	185	Highest strength
Mix 3	15% Fly Ash + 12 M NaOH	0.119	119	Slight reduction

Table 3. Unconfined Compressive Strength Results

The untreated clay exhibited a UCS value of 42 kPa. Considerable improvement in compressive strength was observed after geopolymer stabilization.

6.2 Discussion

The increase in UCS is attributed to geopolymerization reactions occurring between fly ash and alkaline activator. Dissolution of silica and alumina from fly ash resulted in the formation of aluminosilicate gel, which enhanced particle bonding and reduced void spaces within the soil matrix. The 5% fly ash mixture showed moderate improvement due to insufficient reactive material for complete geopolymerization. The 10% fly ash with 10 M NaOH mixture produced maximum strength because of optimum geopolymeric gel formation and improved interparticle bonding. The 15% fly ash

mixture exhibited slight reduction in strength compared to the optimum mix. Excessive fly ash content may reduce effective soil–binder interaction and hinder uniform geopolymer bonding. The stabilized soil also exhibited improved stiffness and load-bearing capacity. Reduction in plasticity and enhanced durability indicate the effectiveness of fly ash–based geopolymer stabilization for expansive clay.

7. CONCLUSIONS

Based on the experimental investigation, the following conclusions are drawn:

1. Fly ash–based geopolymer stabilization significantly improved the strength and geomechanical behavior of expansive clay.
2. The untreated clay exhibited a UCS value of 42 kPa, whereas stabilized specimens showed substantial strength enhancement.
3. The optimum mix containing 10% fly ash with 10 M NaOH produced the highest UCS value of 185 kPa.
4. The optimum geopolymer stabilized mix achieved approximately 340% increase in compressive strength compared to untreated clay.
5. The geopolymerization process improved soil stiffness, reduced plasticity, and enhanced load-bearing capacity.
6. Excessive fly ash content beyond the optimum level caused slight reduction in strength due to non-uniform bonding.
7. Fly ash–based geopolymer stabilization is an environmentally sustainable alternative to traditional stabilizers such as cement and lime.
8. The study confirms the potential application of geopolymer stabilized clay in pavement subgrades, embankments, foundations, and other geotechnical structures.

8. FUTURE SCOPE

Future research may focus on:

1. Long-term durability studies under environmental exposure.
2. Microstructural analysis using SEM, XRD, and FTIR.
3. Swell reduction behavior of geopolymer stabilized clay.
4. Numerical modeling using PLAXIS.
5. Field-scale implementation and performance evaluation.
6. Optimization of curing conditions and activator ratios.

REFERENCES

1. Mahedi, M., Çetin, B., White, D. J., 2020, “Cement, Lime, and Fly Ash in Stabilizing Expansive Soils: Performance Evaluation and Comparison,” *Journal of Materials in Civil Engineering*, Vol. 32, No. 7.
2. Al-Gharbawi, A. S. A., Najemalden, A. M., Fattah, M. Y., 2023, “Expansive Soil Stabilization with Lime, Cement, and Silica Fume,” *Applied Sciences*, Vol. 13, No. 1.
3. Almuaythir, S., Zaini, M. S. I., Hasan, M., Hoque, M. I., 2024, “Sustainable Soil Stabilization Using Industrial Waste Ash: Enhancing Expansive Clay Properties,” *Heliyon*, Vol. 10.
4. Zaini, M. S. I., Hasan, M., 2024, “Stabilization of Expansive Soil Using Silica Fume and Lime,” *Construction Journal*.
5. Onyelowe, K. C., et al., 2021, “Stabilization of Expansive Clayey Soil with Optimum Percentages of Lime, Fly Ash, and Micro-Silica,” *Journal of Engineering and Applied Sciences*.
6. Zand, A. R., Jafarzadeh, M., Abbasnejad, M., 2023, “Combined Effect of Lime, Fly Ash, and Nanoparticles on Expansive Soil Stabilization,” *Construction and Building Materials*, Vol. 380.
7. Wang, Z., Li, J., Zhou, C., Zhang, H., 2020, “Experimental Study on Expansive Soil Modified by Industrial Wastes and Lime under Freeze–Thaw Cycles,” *Cold Regions Science and Technology*, Vol. 170.
8. Sarkar, R., Raghuvanshi, V., Singh, P. K., 2019, “Performance of Expansive Soil Stabilized with a Blend of Waste Materials: A Review,” *International Journal of Geosynthetics and Ground Engineering*, Vol. 5.
9. Jiang, N., Wang, C., Wang, Z., Li, B., 2021, “Strength and Microstructure of Cement-Stabilized Soft Clay Admixed with Silica Fume,” *Materials*, Vol. 14.

10. Xu, L., Wang, X., Qi, Y., Yuan, C., Ding, Z., Xu, R., 2024, “Strength Model for Cement-Stabilized Marine Clay: SEM Image Analysis and Microstructural Insights,” *Journal of Marine Science and Engineering*, Vol. 13.
11. Indiramma, P., Sudharani, R., 2020, “Utilization of Fly Ash and Lime to Stabilize the Expansive Soil: An Experimental Study,” *Case Studies in Construction Materials*, Vol. 13.
12. Türköz, M., 2021, “Effect of Silica Fume as a Waste Material for Sustainable Soil Stabilization,” *Sustainability*, Vol. 13.
13. Barman, D., 2022, “Stabilization of Expansive Soils Using Chemical Additives: A Review,” *Journal of Rock Mechanics and Geotechnical Engineering*, Vol. 14.
14. Zada, U., Haleem, K., Abbas, A., 2021, “Re-Utilization of Stone Industry Waste Materials for Stabilization of Expansive Soil,” *NUST Journal of Engineering Sciences*, Vol. 14.
15. Nadeem, M., 2024, “Performance Evaluation and Microstructural Assessment of Industrial Solid Waste for Soil Stabilization,” *Advances in Civil Engineering*, Vol. 2024.
16. Al-Kalili, A. M., 2022, “A Review on Expansive Soils Stabilized with Different Pozzolanic Materials,” *Engineering Journal*, Vol. 14.
17. Türköz, M., Fattah, M. Y., 2021, “Silica Fume in Stabilization of Swelling Soils: Effects on Bearing Capacity and Swelling Behavior,” *Proceedings of the Institution of Civil Engineers – Ground Improvement*, Vol. 174.
18. Zada, U., 2023, “Recent Advances in Expansive Soil Stabilization Using Industrial By-Products,” *Case Studies in Construction Materials*, Vol. 18.
19. Li, W., 2025, “Synergistic Effects of Cement–Silica Fume Composite on Expansive Soil Stabilization,” *Journal of Building Engineering*, Vol. 82.
20. Di Sante, M., 2025, “Combined Use of Fly Ash and Lime to Stabilize Problematic Soils: Experimental and Microstructural Evidence,” *Geosciences*, Vol. 15.